Beggs, C., Knibbs, L.D., Johnson, G.R., & Morawska, L.
(2015)
Environmental contamination and hospital-acquired infection: factors that are easily overlooked.
Indoor Air, *25*(5), pp. 462-474.

Environmental contamination and hospital acquired infection: factors that are easily overlooked

Journal:	*Indoor Air*
Manuscript ID:	Draft
Manuscript Type:	Review Article
Date Submitted by the Author:	n/a

Complete List of Authors:	Beggs, Clive; University of Bradford, School of Engineering Knibbs, Luke; University of Queensland, School of Population Health Johnson, Graham; Queensland University of Technology, International Laboratory for Air Quality and Health Morawska, Lidia; Queensland University of Technology, International Laboratory for Air Quality and Health

Keywords:	hospital acquired infection, Airborne infection, aerial dissemination, environmental contamination, MRSA, duct cleaning

Environmental contamination and hospital acquired infection: factors that are easily overlooked

Clive Beggs[1*], Luke D. Knibbs[2], Graham R. Johnson[3], Lidia Morawska[3]

[1] Centre for Infection Control and Biophysics, University of Bradford, Bradford, UK
[2] School of Population Health, The University of Queensland, Herston, QLD 4006, Australia
[3] International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, QLD 4001 Australia

*Corresponding Author:

Prof Clive Beggs
Centre for Infection Control and Biophysics
School of Engineering, Design & Technology
University of Bradford
Bradford
West Yorkshire
BD7 1DP
United Kingdom

email: c.b.beggs@bradford.ac.uk, Tel: +44(0)1274 233679, Fax: +44(0)1274 234124

Keywords: hospital acquired infection; airborne infection; aerial dissemination; environmental contamination; MRSA; duct cleaning

Implications of work:

One of the main reasons why nosocomial infection is such a major problem is a widespread failure to recognise that the transmission of infection in hospitals involves complex systems, which are influenced by many factors. This explains why 'single-track' infection control strategies have largely proven to be unsuccessful. In this paper we discuss this issue and demonstrate that a multidisciplinary (multi-track) approach is likely to be more successful. We also evaluate the much overlooked issue of the aerial dissemination of bacteria in hospital wards and demonstrate that this is an important route by which contamination of the clinical environment occurs.

Environmental contamination and hospital acquired infection: factors that are easily overlooked

Abstract

There is an ongoing debate about the reasons for, and factors contributing to healthcare-associated infection (HAI). Different solutions have been proposed over time to control the spread of HAI, with more focus on hand hygiene than on other aspects such as preventing the aerial dissemination of bacteria. Yet, it emerges that there is a need for a more pluralistic approach to infection control; one that reflects the complexity of the systems associated with HAI, and involves multidisciplinary teams including hospital doctors, infection control nurses, microbiologists, architects, and engineers with expertise in building design and facilities management. This paper reviews the knowledge base on the role that environmental contamination plays in the transmission of HAI, with the aim of raising awareness regarding infection control issues that are frequently overlooked. From the discussion presented in the paper it is clear that many unknowns persist regarding aerial dissemination of bacteria, and its control via cleaning and disinfection of the clinical environment. There is a paucity of good quality epidemiological data, making it difficult for healthcare authorities to develop evidence-based policies. Consequently, there is a strong need for carefully designed studies to determine the impact of environmental contamination on the spread of HAI.

Environmental contamination and hospital acquired infection: factors that are easily overlooked

1.0 Introduction

In recent years there has been increased awareness that microbial contamination of the clinical environment might contribute to the spread of healthcare-associated infection (HAI) (Dancer, 2009, NHS, 2007, Boyce, 1997, Dancer, 2004, Dancer, 2008). This has led to an increased emphasis on surface disinfection and ward cleaning, with some authorities placing a statutory obligation on hospitals to ensure that the clinical environment is clean and well maintained (NHS, 2007). While this has made the cleaning and disinfection of hospital wards a higher priority, the role that environmental contamination plays in the transmission of HAI is poorly understood. Indeed, there is little firm epidemiological evidence to support the widely-held and intuitive belief that cleaner hospitals result in fewer infections (Rhame, 1998, Dancer, 2009, Dancer, 2008). Notwithstanding this, there is considerable evidence that the touching of contaminated surfaces by healthcare workers (HCWs) frequently results in the transient colonization of hands or gloves (Boyce, 1997, Hayden, 2008, Bhalla, 2004, Ray, 2002, Duckro, 2005). This suggests that there is a link between surface contamination and transient colonisation of the hands of HCWs. In fact, numerous studies have implicated contamination of the clinical environment in outbreaks of Gram-positive (Malamou-Ladas, 1983, Hota, 2004, Fawley, 2001, Kumari, 1998, Hardy, 2006, Cotterill, 1996) and Gram-negative (Beggs, 2006a, Das, 2002, Weernink, 1995, Allen, 1987, Sherertz, 1985, McDonald, 1998, Breathnach, Engelhart, 2002) bacterial infection. However, while much effort has been expended investigating this issue, most of this has been detective work undertaken in response to specific hospital outbreaks. By comparison, very few controlled trials have been undertaken, with the result that the contribution made by environmental contamination to the overall body of HAI is difficult to quantify and characterize. It is therefore difficult to address with confidence, even basic questions regarding the cleanliness of hospitals. For example, it is not known which ward surfaces should be cleaned or disinfected, and how often such cleaning is required in order to minimise HAI rates. Indeed, it is not known if heavily contaminated surfaces such as hospital ventilation ducts, (which can accumulate particulate debris to a depth of several millimetres) pose any threat to the safety of patients. Consequently, healthcare authorities have great difficulty specifying meaningful performance criteria for general hospital cleanliness.

To explore the role of environmental contamination in the transmission of infection within healthcare facilities, this paper aims to highlight infection control issues relating to building design and facilities management that have been overlooked, but might be worthy of further investigation. We limit our scope to sources of bacterial and fungal infection, as these have been more extensively described in the literature than viral pathogens.

2.0 Gulf between disciplines

Traditionally, infection control has been the sole preserve of hospital doctors, infection control practitioners and microbiologists. However in recent years other professionals such as engineers have become involved in infection control, primarily because of their expertise in building design, facilities management, and modelling airflows within and between room spaces. In addition, many commercial organizations have developed hygiene related products for use in the healthcare sector. This increased activity has led to new insights into the transmission of some HAIs. However, while engineers and physical scientists have been able to make significant contributions to the infection control knowledge base, a gulf in thinking still exists between these professionals and hospital clinicians. This reflects the different approaches inherent in these different occupations and is exemplified by a general belief amongst clinicians that the battle against HAI can be won only through greater hand hygiene compliance. Conversely, engineers and manufacturers tend to believe that gadgets and technical fixes might offer the optimum solution. This has polarized the debate, with clinicians tending to be very sceptical of infection control strategies not primarily focused on hand hygiene compliance, despite the fact that several studies have shown that the efficacy of hand hygiene measures can be severely limited by other factors (Beggs, 2006b, Beggs, 2008b, Beggs, 2009, Silvestri, 2005, Talon, 2009). A middle ground between the two viewpoints that takes a ‘whole of system’ approach to HAI control would be able to capitalise on the expertise of all involved. Unfortunately, this has been conspicuous in its absence to date.

3.0 Complexity of the systems associated with HAI

HAIs arise from complex systems influenced by many factors, not the least of which are the biological characteristics of the infectious agents involved. In particular, the logistics associated with the management of patients and staff appear to be critical (Beggs, 2006b). This complexity has largely been ignored by many in the infection control community, with the result that there has been a tendency to rely on single-measure strategies rather than taking a more holistic approach. However, the evidence suggests that single-measure strategies are not sufficient and that a more multi-faceted approach is required. Take for example the contrasting experiences of the health services in the Netherlands and UK. The Netherlands was quick to introduce a search-and-destroy (S&D) policy to counteract the emergence of drug resistant bacteria such as methicillin-resistant *S. aureus* (MRSA). The S&D policy was introduced as soon as cases of methicillin resistance were reported, although no official protocol existed until 1989 (Dekker, 2010). As the name implies, the Dutch authorities employed a comprehensive strategy that sought to isolate, contain and destroy MSRA whenever an infection was suspected or diagnosed. As such, the main focus of the strategy was on the screening and isolation of patients considered to be at increased risk for the carriage of MRSA (van Rijen, 2009). All suspected patients were isolated and only released if cultures proved negative. When cultures were positive, the bacteria were first eradicated before the patient was released. In addition, hospital employees that had unprotected contact with MRSA positive patients were screened and prohibited from returning to work until they were culture negative (Dekker, 2010). This S&D strategy proved to be highly effective, maintaining the level of bacteraemia caused by MRSA at very low levels (≤1%) compared with other European countries that in some cases reached levels of up to 50% (Tiemersma, 2005). Similar screening and isolation strategies were adopted by healthcare trusts in the UK, but these were relaxed or abandoned in 1995 because of a lack of suitable isolation rooms, and also because ward closures and the cohorting of staff and patients caused considerable clinical disruption (Farrington, 1998). Instead, the UK focused on hand hygiene measures alone to fight MRSA – a policy encapsulated in the *Cleanyourhands* campaign (Stone, 2012). Unlike the Dutch experience, this policy resulted in a steady year-on-year increase in deaths associated with MRSA in England and Wales from 1993 to 2006, peaking at >1600 in 2006 (Pearson, 2009). Likewise, deaths associated with *Clostridium difficile* rose steadily from <1000 in 1999 to >8000 in 2007 (Pearson, 2009). While there is some evidence that the *Cleanyourhands* campaign, initiated in 2004, was responsible for stopping the steady rise of HAIs (Stone, 2012), it was not until a raft of additional infection control measures were introduced around 2007 that HAI rates began to fall. With the introduction of care bundles (i.e. simple infection control guidelines for placing catheters, invasive lines and ventilator tubes); widespread deep cleaning of wards; cohorting of staff and patients; and improved screening of patients; MRSA and *C. difficile* infection rates fell by >50% (HPA, 2012b, HPA, 2012a). Collectively, this highlights the need for a more pluralistic approach to infection control; one that reflects the complexity of the systems associated with HAI.

4.0 Aerial dissemination

One interesting difference between the Dutch and British approaches to the control of MRSA is that the former assumed that MRSA can be disseminated by the airborne route, whereas the latter did not, as this route of transmission is generally not considered to be of great importance. Consequently, in the Netherlands MRSA isolation rooms are required to have an antechamber and to be negatively pressurized (van Rijen, 2009), whereas in the UK, patients colonized with MRSA tend to be *barrier nursed* through placement in ward side rooms and the implementation of additional precautions to prevent the spread of infection. This highlights the tension that exists regarding the airborne transmission of infection in hospitals (Beggs, 2003a) – something that clinicians in many countries believe is of negligible importance compared to the spread of infection via the handborne route (Rhame, 1998, Ayliffe, 1999). Yet there is a large body of evidence which suggests that both Gram-negative and Gram-positive pathogens are frequently disseminated by the aerial route in the clinical environment. Contaminated clothing and bedding of colonized patients release *S. aureus* into the air when disturbed (Shiomori, 2002, Noble, 1965, Solberg, 1965). Bed-making in particular liberates large numbers of particles (Roberts, 2006), many of which carry staphylococci into the air and these are then deposited on surfaces within the environment (Shiomori, 2001, Shiomori, 2002, Noble, 1962). For example Rutala et al (Rutala, 1983) investigated a MRSA outbreak in a burn unit and found that MRSA accounted for 16% of all bacterial isolates sampled from the air, and 31% of the isolates cultured from elevated surfaces. In another study Shiomori et al (Shiomori, 2002), sampling the environment around MRSA colonized and infected patients under normal conditions, found an average of 4.7 cfu/m^3 MRSA-carrying particles in the air near infected patients; however during bed making this figure increased to 116 cfu/m^3, confirming that this activity results in considerable aerosolization of particles containing staphylococci. Similarly, it has been demonstrated that *Acinetobacter* spp. (Houang, 2001, Beggs, 2006a, Allen, 1987, Das, 2002, Gerner-Smidt, 1987, Obbard, 2003, Thornton, 2004) and *C. difficile* (Roberts, 2008) can be readily disseminated into the clinical environment by the aerial route. The different levels of recognition and acknowledgement of such evidence supporting airborne dissemination in the Netherlands and UK may have been a key factor in determining their relative success.

4.1 Surface contamination due to aerial dissemination

The extent to which aerial dissemination of bacteria contributes to surface contamination in hospitals has received little attention. Of the few studies undertaken, most have been carried out under controlled conditions in aerosol chambers (King, 2012, Hathway, 2007, Wong, 2010), with only a handful of studies linking particle dissemination with clinical activities (Roberts, 2006, Hathway, 2011, Ayliffe, 1999, Greene, 1960). Consequently, while it is known that aerial dissemination can result in surface contamination, there is little quantitative data on deposition rates and their variation, with which to make clinical judgments. It is however possible to make a rough estimate of particle deposition rates based on published data and using reasonable assumptions. For example, consider a 10 $\times$ 8 $\times$ 2.7 m ward room containing four patients (ignoring the presence of visitors, doctors, nurses, etc.), which experiences a ventilation rate of four air changes per hour. Given that an average person is thought to liberate approximately 3 $\times$ 10^8 skin squamae (in the range 4-25 μm (Noble, 1981)) into the air every day (Rhame, 1998), the four patients on the wards would have a combined average liberation rate of 13889 squamae per second. If the air in the room space is well mixed and the squamae evenly distributed, then the calculated steady-state mean concentration of skin squamae in the air would be 57870 squamae/m^3. If it is then conservatively estimated that each squamae carries 10 cfu of bacteria (Lundholm estimated that squamae frequently carry >100 cfu (Lundholm, 1982)), we arrive at a figure of 578700 cfu/m^3 of air. If only 20% of these bacteria carrying particles deposit at an average rate of 2 mm/s (the settling velocity of an 8 μm particle), then a conservative estimate would be that approximately 231 cfu would deposit per 1 m^2 of horizontal surface every second. Of course in reality, the particles would not be evenly distributed throughout the room space, or shed at a constant rate - they would be liberated periodically in great numbers during bed making and other activities. Notwithstanding this, this crude calculation does serve to illustrate an important and much over-looked point; namely, that aerial dissemination must be responsible for widespread surface contamination within the clinical environment. Evidence supporting this supposition comes from a 22-month surveillance study in which air vents and high horizontal surfaces were found to be contaminated with *C. difficile*, suggesting the aerial dissemination of isolates (Fawley, 2001, Fawley, 2003). Furthermore, outbreak strains of MRSA are frequently recovered from elevated surfaces (Rutala, 1983) that are unlikely to have been touched by healthcare personnel, indicating that staphylococci must be transported through the air. Indeed, Boyce et al (Boyce, 1997) found that patients colonized/infected with MRSA frequently contaminated room surfaces, with environmental contamination occurring in the rooms of 73% of MRSA-infected patients.

5.0 Ward cleanliness

Given that aerial dissemination of bacteria must be widespread in hospitals, why then is more attention not paid to this phenomenon? The simple answer to this question is that the clinical relevance of aerial dissemination is not well understood and therefore it is not considered a major problem. Outside of a few countries, notably the Netherlands and some Scandinavian countries, aerial dissemination of bacteria appears to have been largely ignored. One reason for this indifference is that the whole subject of ward cleanliness has generally been viewed as being of secondary importance compared with hand hygiene compliance. While the general public might associate visibly dirty wards with the transmission of MRSA infection, rather surprisingly there is relatively little epidemiological evidence that the environment is important in endemic HAI (Rhame, 1998, Dancer, 2009, Dancer, 2008, Maki, 1982, Collins, 1988, McGowan, 1981). Indeed, in a 2007 paper (Boyce, 2007), the eminent microbiologist JM Boyce felt compelled to start his paper with the words: *"For several decades, there has been considerable controversy over whether or not contaminated environmental surfaces contribute to transmission of healthcare-associated pathogens."* Given that contaminated surfaces can readily contaminate the hands of HCWs (Boyce, 1997, Hayden, 2008, Bhalla, 2004, Ray, 2002, Duckro, 2005), one might wonder why there is any controversy. However, while it is relatively easy to show that colonized and infected patients can readily contaminate the clinical environment, it is much more difficult to demonstrate causality in the reverse direction. Consequently, epidemiological evidence supporting the link between ward cleanliness and HAI has been hard to obtain, with the result that healthcare authorities, hard-pressed by financial constraints, have tended to reduce the numbers of cleaners employed and the hours worked (Dancer, 2008). Furthermore, because the evidence base is sparse, cleaners specifications often focus on the cleaning of the most visible and widely-accepted locations like floors and toilets, rather than cleaning near-patient hand-touch sites, such as bed rails, bedside lockers, and infusion pumps, which are more likely to be of clinical importance (Dancer, 2008). As a result, cleaning of these near-patient surfaces may all too easily be overlooked.

In 2007, partly due to political pressure, but also due recognition that existing infection control policies had failed, the Department of Health in the UK rolled out a comprehensive hospital deep cleaning programme (DoH, 2008). At approximately the same time they also introduced a new national specification for hospital cleanliness (NHS, 2008) and imposed a statutory obligation on healthcare trusts to provide and maintain a clean clinical environment (NHS, 2008) – a noticeable departure from previous policy. Interestingly, the introduction of this policy coincided with a marked reduction in reported MRSA bacteraemia cases, which in England and Wales fell from 4451 in 2007-08 to 1114 in 2011-12 (HPA, 2012b) – something that was matched by a similarly large reduction in *C. difficile* associated infections (HPA, 2012a). This raises an obvious question about the extent to which the change in policy contributed to the reduction in HAI rates. However, this question is not easy to answer, because along with improved cleanliness, the Department of Health also introduced a raft of other measures, including improved strategies for placing and monitoring catheters and invasive lines, together with a continued push to improve hand hygiene compliance (*Cleanyourhands* campaign). Indeed, in a recent article, Stone et al (Stone, 2012) attributed the reductions in MRSA and *C. difficile* infection rates almost entirely to the *Cleanyourhands* campaign, which was commenced in 2004 - despite the fact that *C. difficile* infection rates did not start to fall until 2007. Noticeably, no mention was made, or analysis undertaken, of the contribution of improved ward cleanliness to the reduction in infection rates. Consequently, while intuitively one might feel that environmental contamination must influence HAI rates, concrete epidemiological evidence to this effect remains elusive due to the difficulty in disentangling the role of other factors. Notwithstanding this, there is evidence that hardy pathogens, such as *S. aureus* can be widely disseminated throughout the clinical environment via the hands of HCWs. Oelberg *et al* (Oelberg, 2000) using a viral DNA marker to inoculate a single telephone in a neonatal intensive care unit (NICU), observed that inanimate surfaces throughout the NICU rapidly became contaminated, with the number of positive sites peaking after only 8 hours. Similarly, Duckro *et al* (Duckro, 2005) found vancomycin-resistant enterococci (VRE) to be rapidly disseminated around the clinical environment via HCW-surface interactions. Furthermore, Wilson et al (Wilson, 2004) observed a strong correlation between the presence of MRSA-colonized or –infected patients and air samples yielding MRSA in an ICU, suggesting widespread aerial dissemination. Given that contact with contaminated surfaces can readily lead to transient colonization of the hands of HCWs (Boyce, 1997), there is good reason to believe that hospital cleanliness is likely to have an impact on HAI rates.

6.0 Hospital ventilation and duct contamination

Most modern hospital buildings utilize mechanical ventilation air conditioning systems in order to maintain a comfortable environment for patients and staff. These systems contain large stretches of ductwork in which particulate matter can deposit and accumulate. Consequently, ducts in hospitals can become highly contaminated (see Figure 1). In recent years concern has been expressed about the risks posed by contaminated mechanical ventilation ductwork in hospital buildings. Yet, relatively little research has been carried out into the health risks associated with contaminated ventilation ductwork, particularly in healthcare facilities, with the result that little epidemiological evidence exists.

While both supply and extract ducts may become heavily contaminated, in hospital buildings it is important to distinguish between the two. This is because the nature of the contamination is likely to be very different in the two types of ductwork. In supply ducts, because the air comes from a mixture of outdoor and filtered return air, fungal species are likely to predominate, whereas in the return air ducts, which extract from the ward spaces, contamination is likely to be predominately bacterial in nature. Of course, if the air is recirculated, as is frequently the case, then the bacterial pathogens from the ward space, such as MRSA, are likely to contaminate the supply duct and this might pose a greater hazard. Dust from occupied sections of buildings is largely comprised of skin squamae, and can accumulate in return ducts, especially when the air velocity is low (Batterman, 1995). It is therefore important when considering the subject of ductwork contamination to also consider the type of ventilation system in use, as this may have a bearing on the risk. Clearly if the recirculation of room air is permitted, then there is a greater likelihood of bacterial pathogens, being widely distributed around a healthcare facility via the mechanical ventilation system. Indeed, a number of studies relating to the transmission of tuberculosis (TB) have shown this to be the case (Nardell, 1991, Beggs, 2003b, Houk, 1980).

Guidelines regarding the recirculation of air in healthcare settings vary greatly (Beggs, 2008a). For example, the American Institute of Architects (AIA) guidelines permit recirculation of ward air (AIA, 2001), whereas those for the United Kingdom in HTM 2025 strongly discourage the use of recirculation systems (NHS, 1994). Because recirculation of air is permitted, in the United States the air supplied to patients in general wards must be first pre-filtered (minimum efficiency reporting value [MERV] 7, 30% dust spot efficiency), and then filtered to a MERV 14 or 15 standard (90% to 95% dust spot efficiency) before delivery to the ward space (ASHRAE, 2003). This standard of filtration ensures 85% to 95% collection efficiency for 0.3 to 1.0 μm particles and >90% efficiency for >1.0 μm particles. Given that skin squamae are generally 4 to 25 μm in size, this level of filtration should ensure that the air supplied to the ward space is relatively clean, despite the fact that a large proportion of this air may be recirculated. By comparison in the United Kingdom, where ward mechanical ventilation systems tend to be full fresh air, HTM 2025 is somewhat vague on the subject of filtration. Indeed, it simply specifies EU5 filters (50% dust spot efficiency) for ‘‘general applications where decor protection is not critical’’ and EU6 filters (70% dust spot efficiency) for general applications where decor protection is particularly important, making no reference to clinical requirements (NHS, 1994), reflecting the lower perceived risk.

6.1 Ductwork contamination

Given that heavily contaminated ductwork such as that shown in Figure 1 can be found in hospital buildings, one might naturally assume that it poses a significant health hazard. However, the reality is that there are very little data directly relating environmental contamination of this type to adverse health effects (Kuehn, 2003). One reason for this might be that mechanical ventilation systems effectively act as a sink removing microbial particles from ward air – in effect, they act like a giant filter. If microbial particles are deposited within a ductwork system, then by definition they are removed from the air stream that enters the ward space. So in effect, the ductwork traps larger airborne particles preventing them from being distributed around the clinical environment. While this might be considered beneficial, there is also a potential down-side. If microbial particles from the ductwork become re-suspended in the air for any reason, then they will be readily dispersed into the ward spaces. While relatively little is known about the re-suspension of bacterial matter, the same cannot be said for fungal spores that are uniquely adapted for aerial dissemination. Unlike bacterial matter, which generally requires the intervention of some mechanical force to create an aerosol, fungal spores are naturally disseminated by the airborne route, and so can easily re-enter the air stream within ventilation ducts. Given that hospital air conditioning and ductwork systems can become heavily contaminated with nosocomial fungal pathogens, such as *Aspergillus* species (Lutz, 2003, Curtis, 2005, Lentino, 1982), there is reason to believe that ductwork colonized with fungal species might pose an infection risk, especially to immunocompromised patients (Buttner, 1999).

There is evidence implicating contaminated ventilation systems with fungal infections in immunocompromised patients. Walsh and Dixon (Walsh, 1989) cited contaminated ventilation systems as a common source of invasive aspergillosis, while Lentino et al (Lentino, 1982) implicated contaminated window mounted air conditioning units in an outbreak of pulmonary aspergillosis. In another study, Lutz et al (Lutz, 2003) identified mold contamination in an operating theatre air-handling system as the source of *Aspergillus* infections amongst post-surgical patients. They found that insulation material in variable-air-volume (VAV) units had become wet and had subsequently become colonized with several *Aspergillus* species. Insulation and filter media appear particularly vulnerable to fungal degradation when wet or under conditions of high humidity. Simmons and Crow (Simmons, 1995) found substantial growth of *Aspergillus* species on cellulosic filters at relative humidities >70%, and Maus et al (Maus, 2001) observed significant growth of *Aspergillus niger* on used filters at relative humidities >85%.

With regard to the aerial dissemination of *Aspergillus* conidia, the case study described by Lutz et al (Lutz, 2003) highlights the importance of using terminal filtration in locations where immunocompromised patients might be vulnerable to infection. In this case, Lutz et al identified the fact that variable air volume (VAV) units were mounted downstream of final filters as an issue of concern. When the insulation material in the ductwork became damp and degraded there was no barrier to filter the spores, and they were readily disseminated into the operating theatre. Given that *Aspergillus* conidia have diameters in the region 2-4 μm (Lutz, 2003), somewhat smaller than skin squamae, it may be necessary to install high-performance terminal filtration if the dissemination of spores is to be prevented – something highlighted in a study by Oren et al (Oren, 2001) who reported on an outbreak of pulmonary aspergillosis associated with construction activity. They found that airborne concentrations of *Aspergillus* species rose to a mean value of 15 cfu/m^3 in wards near a construction site. However, the installation of high-efficiency particulate air (HEPA) filters in hematological ward reduced the mean count to 0.18 cfu/m^3 and eliminated invasive pulmonary aspergillosis completely.

6.2 Ductwork cleaning

Concerns regarding potential infection risks posed by contaminated ducting have led to a rise in the number of contractors offering specialist ductwork cleaning services to healthcare authorities. However, the evidence base of the efficacy of these measures in hospitals is limited. A somewhat larger body of evidence exists in relation to duct cleaning in residential and non-industrial commercial buildings, and this was recently reviewed with an aim of answering the question: *is ventilation duct cleaning useful?* (Zuraimi, 2010). The review, which employed strict inclusion criteria to assure that only peer reviewed, well designed and relevant papers were considered, came to several important conclusions. It firstly confirmed the existence of evidence that ventilation ducts are often contaminated with dust and provide conditions for microbiological growth, and that this happens under normal operating conditions. However, no field studies have conclusively correlated concentration of indoor pollution with duct contamination, despite controlled experiments showing that there is a plausible basis for this happening. The review also examined the available duct cleaning methodologies and showed that some of them are very efficient. However, again, it was unable to find consistent evidence that there is an improvement in indoor air quality after cleaning of the ducts. In fact, some of studies concluded that the opposite is the case, and that post-cleaning indoor concentrations are higher than pre-cleaning.

There is a disparity between the lack of evidence that duct cleaning can improve occupants' health or symptoms, and some suggestive evidence from epidemiological studies highlighting the association of dirty ducts with higher risk of symptoms. In general, the review demonstrated that that there is a need for balance between duct cleanliness and negative effects related to the process of cleaning. Nevertheless, the study demonstrated that the body of the evidence on many of the aspects discussed is still small and identified specific areas requiring further research. While there are large differences between residential and commercial buildings in their purpose, design and operation, it is expected that the general conclusion on duct cleaning in such buildings is also generally applicable to hospital buildings, and that the knowledge gaps on the impact of duct cleaning on hospital building are even greater. Consequently, because the evidence base is sparse, healthcare authorities find it difficult to develop objective standards.

Most parts of ventilation systems can support microbial growth (Batterman, 1995), but frequently damp sections of ventilation air handling equipment and ducting most effectively promote mold growth, particularly *Aspergillus fumigatus* and *Aspergillus flavus*. This is especially true in areas where the primary role of the air handler is cooling, leading to substantial water condensation (Horner, 2006). These species are also present in accumulated dust inside ducts. There is evidence to suggest that mechanical brushing is more efficient at removing such dust from metal ducts and compressed air cleaning is more efficient for plastic ducts, and that reductions of 75 to 94% in surface dust levels can be achieved under field conditions (Holopainen, 2003). Of course, it is critical that the potential for resuspension of colonized dust and its liberation into supply air be minimized. Most mechanical brushing systems also incorporate a vacuum collection device, but there is potential for fugitive dust to reach indoor areas (Zuraimi, 2010). Chemical disinfection treatments (biocides, ozone, etc.) may be required to deal with substantial fungal and bacterial growth. However, these can pose a potential health risk in their own right (Zuraimi, 2010). The health risk-benefit balance for duct cleaning is not clear, at least in non-healthcare indoor environments (Zuraimi, 2010). Given the specific nature of healthcare settings, the large number of potential infection sources within them, and the susceptible nature of their occupants, it is plausible that carefully performed and appropriate duct cleaning could reduce HAI risk. However, the evidence base on this topic is very limited, and there is a strong need for well-performed studies linking duct cleaning with health outcomes. In the meantime, it is prudent to prevent or limit microbial contamination in the first instance, through the use of ultraviolet germicidal irradiation (UVGI) in air handlers and ducting, for example (Horner, 2006).

7.0 Discussion and Conclusions

The discussion above highlights the considerable hole in the knowledge base regarding the role that environmental contamination plays in the transmission of HAI. Not only is there no agreement on the risks posed by specific issues such as ductwork contamination, there is little quantifiable evidence regarding the benefits, or otherwise, of cleaning and disinfecting hospital wards, despite a general consensus that it is probably a good thing to do. Because it is difficult to quantify, the impact of hospital cleanliness is easily ignored. For example, the substantial fall in HAIs in the UK since 2007 has been attributed by some (Stone, 2012), almost entirely to the *Cleanyourhands* campaign, despite the introduction of care bundles and hospital deep cleaning at approximately that time. Although hand hygiene is a key infection control measure of great importance, there is growing evidence that a multi-faceted approach is necessary. Evidence from several mathematical simulation studies (Beggs, 2006b, Beggs, 2008c, Beggs, 2009) suggests that poor hand hygiene compliance is only one factor in the spread of HAI, and that other factors must be at work. The UK experience since 2007 would tend to support this opinion. The introduction of a multi-faceted approach involving the introduction of: patient screening; cohorting of patients and nurses; careful use of antibiotics; improved placement and management of intravenous lines and catheters; improved management of ventilated patients; ward deep cleaning; and greater emphasis on hospital cleanliness; has led to a dramatic fall in MRSA and *C. difficile* infection rates. However, while great improvements have been made it is difficult to say which particular measures have been the most effective. So the contribution of improved ward cleanliness to the overall reduction in HAIs is difficult to quantify. Consequently, more research is needed to understand and quantify the role that ward cleaning plays in preventing HAIs.

One advance in recent years has been the trend towards a more multi-disciplinary approach to infection control. In particular, the involvement of engineers in infection control has led to advances in the application of technologies such as ultraviolet germicidal irradiation (Noakes, 2007, Beggs, 2002a, Beggs, 2002b, Cairns, 2001, Noakes, 2004, Noakes, 2006, Beggs, 2000, Beggs, 2006c), negative air ionization

(Kerr, 2006, Fletcher, 2007, Fletcher, 2008), and hydrogen peroxide terminal disinfection (Otter, 2007, Otter, 2006, Otter, 2009, Otter, 2008). While these technologies have merit, engineers can make the mistake of thinking that HAIs can be eliminated using a quick-fix technological solution. Indeed, many devices have not delivered reductions in HAI, primarily because their inventors failed to understand the complexity of the epidemiological systems associated with HAI. Having said this, if used appropriately as part of a multi-faceted approach to infection control, some of these environmental technologies may prove to be an important part of the solution. It is critical for engineers and others involved in technological solutions to bear in mind that the ultimate success or failure of an intervention is likely to depend more on the human element than the capability of the technology.

The simple calculation presented in section 4.1 above, suggests that aerial dissemination of bacteria may be a much greater problem than has been hitherto recognized. If staphylococci are being deposited onto surfaces from air at a rate >200 cfu/m^2 per second, as the calculation indicates, then this would suggest that aerial dissemination may be the principal mechanism by which contamination of the clinical environment occurs. Although the clinical relevance of aerial dissemination is not known, there is good reason for believing that it may be important. Ayliffe et al (Ayliffe, 1999) reported that sterile gauze and forceps laid on a horizontal surface, became readily contaminated by bacteria through aerial dissemination after bed making and curtain shaking. Das et al. (Das, 2002) implicated heavily contaminated bed curtains in an outbreak of *Acinetobacter baumanii*, which when moved promoted the airborne spread of *Acinetobacter* species. Similarly, Weernink et al. (Weernink, 1995) implicated feather pillows in the aerial dispersal of *Acinetobacter* species. Boyce et al (Boyce, 1997) found that 42% of personnel who had no direct contact with MRSA patients, but had touched contaminated surfaces within the ward space, contaminated their gloves with MRSA. Furthermore, Noble et al. (Noble, 1981) found that the size distribution of particles containing *S. aureus* was approximately 4–25 μm, which is roughly the size of skin squamae and well in excess of the size of single *S. aureus* cells (i.e. about 1 μm diameter). Noble et al. therefore surmised that most of the airborne *S. aureus* organisms were carried on skin squamae. Given that humans liberate approximately 3×10^8 skin squamae into the air every day (Rhame, 1998), Noble et al. concluded that in many people a closed loop exists; contaminated skin squamae are released into the air; they become impacted on the nasal turbinates; *S. aureus* grows on the nasal mucosa; hands then touch the nose and *S.*

aureus bacteria are transferred to the skin; they colonise the skin and are ultimately disseminated back into the air on skin squamae.

Given increased emphasis on hospital hygiene in recent years, it is surprising that the microbial contamination that readily accumulates in air handling units and ventilation ducts is often overlooked. Intuitively, one would think that heavy contamination of such systems poses some sort of threat to patient safety. However, because few epidemiological studies have been undertaken specifically to investigate this subject, there is little evidence to substantiate this claim. Consequently, there is need for carefully designed studies to investigate the clinical impact of contaminated ductwork.

Acknowledgement

At the Healthy Buildings 2012 conference in Brisbane in July 2012 a debate was conducted and attended by many experts on infection control and building design. This debate explored the role of environmental contamination in the transmission of infection within healthcare facilities. This paper arises from that debate and we are thankful to all those who contributed to it. In particular we thank the panel members, Tricia Coward, Yuguo Li, Jeremy Stamkos and Erica Stewart for their helpful contributions. This work was also supported by a Queensland University of Technology, IHBI Collaborative Research Development Grant titled, *How transmissible is influenza by the airborne route?*

References

Aia (2001) *Guidelines for design and construction of hospital and health care facilities,* Washington, DC, American Institution of Architects (AIA).

Allen, K.D. and Green, H.T. (1987) "Hospital outbreak of multi-resistant Acinetobacter anitratus: an airborne mode of spread?", *J Hosp Infect*, **9**, 110-119.

Ashrae (2003) *HVAC design manual for hospitals and clinics,* Atlanta, American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE).

Ayliffe, G.A.J., Babb, J.R. and Taylor, L.J. (1999) *Hospital-acquired infection – principles and prevention*, Butterworth-Heinemann.

Batterman, S.A. and Burge, H. (1995) "HVAC systems as emission sourses affecting indoor air quality: a critical review", *HVAC&R Research*, **1**, 61-80.

Beggs, C.B. (2002a) "A quantitative method for evaluating the photoreactivation of ultraviolet damaged microorganisms", *Photochem Photobiol Sci*, **1**, 431-437.

Beggs, C.B. (2003a) "The airborne transmission of infection in hospital buildings: fact or fiction?", *Indoor and Built Environment* **12**, 1-10.

Beggs, C.B. (2003b) "The Airborne Transmission of Infection in Hospital Buildings: Fact or Fiction?", *Indoor and Built Environment*, **12**, 9-18.

Beggs, C.B., Kerr, K.G., Donnelly, J.K., Sleigh, P.A., Mara, D.D. and Cairns, G. (2000) "An engineering approach to the control of Mycobacterium tuberculosis and other airborne pathogens: a UK hospital based pilot study", *Transactions of the Royal Society of Tropical Medicine and Hygiene*, **94**, 141-146.

Beggs, C.B., Kerr, K.G., Noakes, C.J., Hathway, E.A. and Sleigh, P.A. (2008a) "The ventilation of multiple-bed hospital wards: review and analysis", *Am J Infect Control*, **36**, 250-259.

Beggs, C.B., Kerr, K.G., Snelling, A.M. and Sleigh, P.A. (2006a) "Acinetobacter spp. and the clinical environment", *Indoor and Built Environment*, **15**, 19-24.

Beggs, C.B., Noakes, C.J., Shepherd, S.J., Kerr, K.G., Sleigh, P.A. and Banfield, K. (2006b) "The influence of nurse cohorting on hand hygiene effectiveness", *Am J Infect Control*, **34**, 621-626.

Beggs, C.B., Noakes, C.J., Sleigh, P.A., Fletcher, L.A. and Kerr, K.G. (2006c) "Methodology for determining the susceptibility of airborne microorganisms to irradiation by an upper-room UVGI system", *Journal of Aerosol Science*, **37**, 885-902.

Beggs, C.B., Shepherd, S.J. and Kerr, K.G. (2008b) "Increasing the frequency of hand washing by healthcare workers does not lead to commensurate reductions in staphylococcal infection in a hospital ward", *BMC Infect Dis*, **8**, 114.

Beggs, C.B., Shepherd, S.J. and Kerr, K.G. (2008c) "Increasing the frequency of hand washing by healthcare workers does not lead to commensurate reductions in staphylococcal infection in a hospital ward", *BMC Infect Dis*.

Beggs, C.B., Shepherd, S.J. and Kerr, K.G. (2009) "How does healthcare worker hand hygiene behaviour impact upon the transmission of MRSA between patients?: an analysis using a Monte Carlo model", *BMC Infect Dis*, **9**, 64.

Beggs, C.B. and Sleigh, P.A. (2002b) "A quantitative method for evaluating the germicidal effect of upper room UV fields", *J Aero Sci*, **33**, 1681-1699.

Bhalla, A., Pultz, N.J., Gries, D.M., Ray, A.J., Eckstein, E.C., Aron, D.C. and Donskey, C.J. (2004) "Acquisition of nosocomial pathogens on hands after contact with environmental surfaces near hospitalized patients", *Infect Control Hosp Epidemiol*, **25**, 164-167.

Boyce, J.M. (2007) "Environmental contamination makes an important contribution to hospital infection", *J Hosp Infect*, **65 Suppl 2**, 50-54.

Boyce, J.M., Potter-Bynoe, G., Chenevert, C. and King, T. (1997) " Environmental contamination due to methicillin-resistant Staphylococcus aureus: possible infection control implications", *Infect Control Hosp Epidemiol* **18**, 622 – 627.

Breathnach, A.S., Cubbon, M.D., Karunaharan, R.N., Pope, C.F. and Planche, T.D. "Multidrug-resistant Pseudomonas aeruginosa outbreaks in two hospitals: association with contaminated hospital waste-water systems", *J Hosp Infect*, **82**, 19-24.

Buttner, M.P., Cruz-Perez, P., Garrett, P.J. and Stetzenbach, L.D. (1999) "Dispersal of fungal spores from three types of air handling system duct material", *Aerobiologia*, **15**, 1-8.

Cairns, G., Kerr, K.G., Beggs, C.B., Sleigh, P.A., Mooney, L., Keig, P. and Donnelly, J.K. (2001) "Susceptibility of Burkholderia cepacia and other pathogens of importance in cystic fibrosis to u.v. light", *Letters in Applied Microbiology*, **32**, 135-138.

Collins, B.J. (1988) "The hospital environment: how clean should a hospital be?", *J Hosp Infect*, **11 Suppl A**, 53-56.

Cotterill, S. and Al., E. (1996) "An unusual source for an outbreak of methicillin-resistant Staphylococcus aureus", *Journal of Hospital Infection*, **32**, 207 - 216.

Curtis, L., Cali, S., Conroy, L., Baker, K., Ou, C.H., Hershow, R., Norlock-Cruz, F. and Scheff, P. (2005) "Aspergillus surveillance project at a large tertiary-care hospital", *J Hosp Infect*, **59**, 188-196.

Dancer, S.J. (2004) "How do we assess hospital cleaning? A proposal for microbiological standards for surface hygiene in hospitals", *J Hosp Infect*, **56**, 10-15.

Dancer, S.J. (2008) "Importance of the environment in meticillin-resistant Staphylococcus aureus acquisition: the case for hospital cleaning", *Lancet Infect Dis*, **8**, 101-113.

Dancer, S.J., White, L.F., Lamb, J., Girvan, E.K. and Robertson, C. (2009) "Measuring the effect of enhanced cleaning in a UK hospital: a prospective cross-over study", *BMC Med*, **7**, 28.

Das, I., Lambert, P., Hill, D., Noy, M., Bion, J. and Elliott, T. (2002) "Carbapenem-resistant Acinetobacter and role of curtains in an outbreak in intensive care units", *J Hosp Infect*, **50**, 110-114.

Dekker, T.J.A. and Van Den Broek, P.J. (2010) "Successful control of MRSA spread in Dutch Hospitals", *International Journal of Infection Control*, **6**, 1-4.

Doh (2008) From deep clean to keep clean.

Duckro, A.N., Blom, D.W., Lyle, E.A., Weinstein, R.A. and Hayden, M.K. (2005) "Transfer of vancomycin-resistant enterococci via health care worker hands", *Arch Intern Med*, **165**, 302-307.

Engelhart, S., Krizek, L., Glasmacher, A., Fischnaller, E., Marklein, G. and Exner, M. (2002) "Pseudomonas aeruginosa outbreak in a haematology-oncology unit associated with contaminated surface cleaning equipment", *J Hosp Infect*, **52**, 93-98.

Farrington, M., Redpath, C., Trundle, C., Coomber, S. and Brown, N.M. (1998) "Winning the battle but losing the war: methicillin-resistant Staphylococcus aureus (MRSA) infection at a teaching hospital", *QJM*, **91**, 539-548.

Fawley, W.N., Freeman, J. and Wilcox, M.H. (2003) "Evidence to support the existence of subgroups within the UK epidemic Clostridium difficile strain (PCR ribotype 1)", *J Hosp Infect*, **54**, 74-77.

Fawley, W.N. and Wilcox, M.H. (2001) "Molecular epidemiology of endemic Clostridium difficile infection", *Epidemiol Infect*, **126**, 343-350.

Fletcher, L.A., Gaunt, L.F., Beggs, C.B., Shepherd, S.J., Sleigh, P.A., Noakes, C.J. and Kerr, K.G. (2007) "Bactericidal action of positive and negative ions in air", *BMC Microbiol*, **7**, 32.

Fletcher, L.A., Noakes, C.J., Sleigh, P.A., Beggs, C.B. and Shepherd, S.J. (2008) "Air ion behavior in ventilated rooms", *Indoor and Built Environment*, **17**, 173-182.

Gerner-Smidt, P. (1987) "Endemic occurrence of Acinetobacter calcoaceticus biovar anitratus in an intensive care unit", *J Hosp Infect*, **10**, 265-272.

Greene, V.W., Bond, R.G. and Michaelsen, G.S. (1960) "Air handling systems must be planned to reduce the spread of infection", *Mod Hosp*, **95**, 136-144.

Hardy, K.J., Oppenheim, B.A., Gossain, S., Gao, F. and Hawkey, P.M. (2006) "A study of the relationship between environmental contamination with methicillin-resistant Staphylococcus aureus (MRSA) and patients' acquisition of MRSA", *Infect Control Hosp Epidemiol*, **27**, 127-132.

Hathway, E.A., Noakes, C.J., Sleigh, P.A. and Fletcher, L.A. (2011) "CFD simulation of airborne pathogen transport due to human activities", *Building and Environment*, **46**, 2500-2511.

Hathway, E.A., Sleigh, P.A. and Noakes, C.J. (2007) CFD Modelling of Transient Pathogen Release in Indoor Environments due to Human Activity, *Proceedings of the 10th International Conference on Air Distribution in Rooms - Roomvent 2007*, Helsinki.

Hayden, M.K., Blom, D.W., Lyle, E.A., Moore, C.G. and Weinstein, R.A. (2008) "Risk of hand or glove contamination after contact with patients colonized with vancomycin-resistant enterococcus or the colonized patients' environment", *Infect Control Hosp Epidemiol*, **29**, 149-154.

Holopainen, R., Asikainen, V., Tuomainen, M., Bjorkroth, M., Pasanen, P. and Seppanen, O. (2003) "Effectiveness of duct cleaning methods on newly installed duct surfaces", *Indoor Air*, **13**, 212-222.
Horner, W.E. (2006) "Managing building-related Aspergillus exposure", *Medical Mycology*, **44 (Sup. 1)**, S33-S38.
Hota, B. (2004) "Contamination, disinfection, and cross-colonization: Are hospital surfaces reservoirs for nosocomial infection?", *Clin Infect Dis*, **39**, 1182-1189.
Houang, E.T., Chu, Y.W., Leung, C.M., Chu, K.Y., Berlau, J., Ng, K.C. and Cheng, A.F. (2001) "Epidemiology and infection control implications of Acinetobacter spp. in Hong Kong", *J Clin Microbiol*, **39**, 228-234.
Houk, V.N. (1980) "Spread of tuberculosis via recirculated air in a naval vessel: the Byrd study", *Ann N Y Acad Sci*, **353**, 10-24.
Hpa (2012a) Summary points on Clostridium difficile infection (CDI), Health Protection Agency.
Hpa (2012b) Summary points on meticillin resistant staphylococcus aureus (MRSA) bacteraemia, Health Protection Agency.
Kerr, K.G., Beggs, C.B., Dean, S.G., Thornton, J., Donnelly, J.K., Todd, N.J., Sleigh, P.A., Qureshi, A. and Taylor, C.C. (2006) "Air ionisation and colonisation/infection with methicillin-resistant Staphylococcus aureus and Acinetobacter species in an intensive care unit", *Intensive Care Medicine*, **32**, 315-317.
King, M.F., Noakes, C.J., Sleigh, P.A. and Camargo-Valero, M.A. (2012) "Bioaerosol deposition in single and two-bed hospital rooms: a numerical and experimental study", *Building and Environment*.
Kuehn, T.H. (2003) "Airborne infection control in health care facilities", *Journal of Solar Energy Engineering*, **125**, 366-371.
Kumari, D.N., Haji, T.C., Keer, V., Hawkey, P.M., Duncanson, V. and Flower, E. (1998) "Ventilation grilles as a potential source of methicillin-resistant Staphylococcus aureus causing an outbreak in an orthopaedic ward at a district general hospital", *J Hosp Infect*, **39**, 127-133.
Lentino, J.R., Rosenkranz, M.A., Michaels, J.A., Kurup, V.P., Rose, H.D. and Rytel, M.W. (1982) "Nosocomial aspergillosis: a retrospective review of airborne disease secondary to road construction and contaminated air conditioners", *Am J Epidemiol*, **116**, 430-437.
Lundholm, I.M. (1982) "Comparison of methods for quantitative determinations of airborne bacteria and evaluation of total viable counts", *Appl Environ Microbiol*, **44**, 179-183.
Lutz, B.D., Jin, J., Rinaldi, M.G., Wickes, B.L. and Huycke, M.M. (2003) "Outbreak of invasive Aspergillus infection in surgical patients, associated with a contaminated air-handling system", *Clin Infect Dis*, **37**, 786-793.
Maki, D.G., Alvarado, C.J., Hassemer, C.A. and Zilz, M.A. (1982) "Relation of the inanimate hospital environment to endemic nosocomial infection", *N Engl J Med*, **307**, 1562-1566.
Malamou-Ladas, H., O'farrell, S., Nash, J.Q. and Tabaqchali, S. (1983) "Isolation of Clostridium difficile from patients and the environment of hospital wards", *J Clin Pathol*, **36**, 88-92.
Maus, R., Goppelsroder, A. and Umhauer, H. (2001) "Survival of bacteria and mold spores in air filter media", *Atmos Environ*, **35**, 105-113.
Mcdonald, L.C., Walker, M., Carson, L., Arduino, M., Aguero, S.M., Gomez, P., Mcneil, P. and Jarvis, W.R. (1998) "Outbreak of Acinetobacter spp. bloodstream infections in a nursery associated with contaminated aerosols and air conditioners", *Pediatr Infect Dis J*, **17**, 716-722.
Mcgowan, J.E., Jr. (1981) "Environmental factors in nosocomial infection-a selective focus", *Rev Infect Dis*, **3**, 760-769.
Nardell, E.A., Keegan, J., Cheney, S.A. and Etkind, S.C. (1991) "Airborne infection. Theoretical limits of protection achievable by building ventilation", *Am Rev Respir Dis*, **144**, 302-306.
Nhs (1994) Health Technical Memorandum 2025 - Design considerations: Ventilation in healthcare premises, London, NHS Estates.
Nhs (2007) The national specifications for cleanliness in the NHS: a framework for setting and measuring performance outcomes, NHS The National Patient Safety Agency.
Nhs (2008) The national specification for cleanliness in the NHS.

Noakes, C., Sleigh, P.A. and Beggs, C.B. (2007) "Modelling the air cleaning performance of negative air ionisers in ventilated rooms". In: Proceedings of Proceedings of the 10th international conference on air movement in rooms - Roomvent 2007, pp. 1046-1056.

Noakes, C.J., Beggs, C.B. and Sleigh, P.A. (2004) "Modelling the performance of upper room ultraviolet germicidal irradiation devices in ventilated rooms: Comparison of analytical and CFD methods", *Indoor and Built Environment*, **13**, 477-488.

Noakes, C.J., Sleigh, P.A., Escombe, A.R. and Beggs, C.B. (2006) "Use of CFD analysis in modifying a TB ward in Lima, Peru", *Indoor and Built Environment*, **15**, 41-47.

Noble, W.C. (1962) "The dispersal of staphylococci in hospital wards", *J Clin Pathol*, **15**, 552-558.

Noble, W.C. (1981) Dispersal of microorganisms from skin, *Microbiology of human skin*, London, Lloyd-Luke Ltd., 79-85.

Noble, W.C. and Davies, R.R. (1965) "Studies on the Dispersal of Staphylococci", *J Clin Pathol*, **18**, 16-19.

Obbard, J.P. and Fang, L.S. (2003) " Airborne concentrations of bacteria in a hospital environment in Singapore", *Water, Air, and Soil Pollution*, **144**, 333-341.

Oelberg, D.G., Joyner, S.E., Jiang, X., Laborde, D., Islam, M.P. and Pickering, L.K. (2000) "Detection of pathogen transmission in neonatal nurseries using DNA markers as surrogate indicators", *Pediatrics*, **105**, 311-315.

Oren, I., Haddad, N., Finkelstein, R. and Rowe, J.M. (2001) "Invasive pulmonary aspergillosis in neutropenic patients during hospital construction: before and after chemoprophylaxis and institution of HEPA filters", *Am J Hematol*, **66**, 257-262.

Otter, J.A., Chewins, J., Windsor, D. and Windsor, H. (2008) "Microbiological contamination in cell culture: a potential role for hydrogen peroxide vapour (HPV)?", *Cell Biol Int*, **32**, 326-327.

Otter, J.A., Cummins, M., Ahmad, F., Van Tonder, C. and Drabu, Y.J. (2007) "Assessing the biological efficacy and rate of recontamination following hydrogen peroxide vapour decontamination", *J Hosp Infect*, **67**, 182-188.

Otter, J.A. and French, G.L. (2009) "Survival of nosocomial bacteria and spores on surfaces and inactivation by hydrogen peroxide vapor", *J Clin Microbiol*, **47**, 205-207.

Otter, J.A., French, G.L., Adams, N.M., Watling, D. and Parks, M.J. (2006) "Hydrogen peroxide vapour decontamination in an overcrowded tertiary care referral centre: some practical answers", *J Hosp Infect*, **62**, 384-385.

Pearson, A. (2009) "Historical and changing epidemiology of healthcare-associated infections", *J Hosp Infect*, **73**, 296-304.

Ray, A.J., Hoyen, C.K., Taub, T.F., Eckstein, E.C. and Donskey, C.J. (2002) "Nosocomial transmission of vancomycin-resistant enterococci from surfaces", *JAMA*, **287**, 1400-1401.

Rhame, F.S. (1998) The inanimate environment, In: Bennett, J. V. and Brachman, P. S. (eds) *Hospital Infections*, Lippincott-Raven Publishers.

Roberts, K., Hathway, A., Fletcher, L.A., Beggs, C.B., Elliott, M.W. and Sleigh, P.A. (2006) "Bioaerosol Production on a Respiratory Ward", *Indoor and Built Environment*, **15**, 35-40.

Roberts, K., Smith, C.F., Snelling, A.M., Kerr, K.G., Banfield, K.R., Sleigh, P.A. and Beggs, C.B. (2008) "Aerial dissemination of Clostridium difficile spores", *BMC Infect Dis*, **8**, 7.

Rutala, W.A., Katz, E.B., Sherertz, R.J. and Sarubbi, F.A., Jr. (1983) "Environmental study of a methicillin-resistant Staphylococcus aureus epidemic in a burn unit", *J Clin Microbiol*, **18**, 683-688.

Sherertz, R.J. and Sullivan, M.L. (1985) "An outbreak of infections with Acinetobacter calcoaceticus in burn patients: contamination of patients' mattresses", *J Infect Dis*, **151**, 252-258.

Shiomori, T., Miyamoto, H. and Makishima, K. (2001) "Significance of airborne transmission of methicillin-resistant Staphylococcus aureus in an otolaryngology-head and neck surgery unit", *Arch Otolaryngol Head Neck Surg*, **127**, 644-648.

Shiomori, T., Miyamoto, H., Makishima, K., Yoshida, M., Fujiyoshi, T., Udaka, T., Inaba, T. and Hiraki, N. (2002) "Evaluation of bedmaking-related airborne and surface methicillin-resistant Staphylococcus aureus contamination", *J Hosp Infect*, **50**, 30-35.

Silvestri, L., Petros, A.J., Sarginson, R.E., De La Cal, M.A., Murray, A.E. and Van Saene, H.K. (2005) "Handwashing in the intensive care unit: a big measure with modest effects", *J Hosp Infect*, **59**, 172-179.

Simmons, R.B. and Crow, S.A. (1995) "Fungal colonization of air filters for use in heating, ventilating and air conditioning (HVAC) systems", *Journal of Industrial Microbiology*, **14**.

Solberg, C.O. and (1965) "A study of carriers of Staphylococcus aureus", *Acta. Med. Scand.* , **178 (suppl.)**, 436.

Stone, S.P., Fuller, C., Savage, J., Cookson, B., Hayward, A., Cooper, B., Duckworth, G., Michie, S., Murray, M., Jeanes, A., Roberts, J., Teare, L. and Charlett, A. (2012) "Evaluation of the national Cleanyourhands campaign to reduce Staphylococcus aureus bacteraemia and Clostridium difficile infection in hospitals in England and Wales by improved hand hygiene: four year, prospective, ecological, interrupted time series study", *BMJ*, **344**, e3005.

Talon, D., Thouverez, M. and Bertrand, X. (2009) "Is there a threshold above which hand-rub solution consumption is efficient for decreasing MRSA incidence?", *J Hosp Infect*, **72**, 178-179.

Thornton, T., Fletcher, L.A., Beggs, C.B., Elliott, M.W. and Kerr, K.G. (2004) "Airborne microflora in a respiratory ward". In: Proceedings of ASHRAE IAQ Conference.

Tiemersma, E.W., Monnet, D.L., Bruinsma, N., Skov, R., Monen, J.C. and Grundmann, H. (2005) "Staphylococcus aureus bacteremia, Europe", *Emerg Infect Dis*, **11**, 1798-1799.

Van Rijen, M.M. and Kluytmans, J.A. (2009) "Costs and benefits of the MRSA Search and Destroy policy in a Dutch hospital", *Eur J Clin Microbiol Infect Dis*, **28**, 1245-1252.

Walsh, T.J. and Dixon, D.M. (1989) "Nosocomial aspergillosis: environmental microbiology, hospital epidemiology, diagnosis and treatment", *Eur J Epidemiol*, **5**, 131-142.

Weernink, A., Severin, W.P., Tjernberg, I. and Dijkshoorn, L. (1995) "Pillows, an unexpected source of Acinetobacter", *J Hosp Infect*, **29**, 189-199.

Wilson, R.D., Huang, S.J. and Mclean, A.S. (2004) "The correlation between airborne methicillin-resistant Staphylococcus aureus with the presence of MRSA colonized patients in a general intensive care unit", *Anaesth Intensive Care*, **32**, 202-209.

Wong, L.T., Chan, W.Y., Nmui, K.W. and Lai, A.C.K. (2010) "An experimental and numerical study on deposition of bioaerosols in a scaled chamber", *Aerosol Sci Technol*, **44**, 117-128.

Zuraimi, M.S. (2010) "Is ventilation duct cleaning useful? A review of the scientific evidence", *Indoor Air*, **20**, 445-457.

Figure Caption

Figure 1. Typical example of a highly contaminated mechanical ventilation duct. Image courtesy of Total Ventilation Hygiene Pty Ltd and licensed for use in the HB2012 presentations and associated media.

Figure 1. Typical example of a highly contaminated mechanical ventilation duct. Image courtesy of Total Ventilation Hygiene Pty Ltd and licensed for use in the HB2012 presentations and associated media.
151x113mm (96 x 96 DPI)